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Research Article

The monetary counterflow. A regenerative model for estuarine ecosystems

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Abstract

This study evaluates the ecological and economic sustainability of the Mai Po Marshes, a Ramsar-designated wetland in Hong Kong, using emergy analysis and a novel monetary counterflow model. The objective is to determine whether financial inflows function as a regenerative counterflow by reinvesting in natural and social capital. The analysis employs standard emergy accounting methods to compute key sustainability indicators, including the Investment Ratio (IR), Environmental Loading Ratio (ELR), Yield Ratio (YR), and Emergy Density (ED). It also introduces a new metric, the Net Monetary Flow Rate (NMFR), to assess the balance between economic returns and environmental costs. Results indicate a total emergy output of 26.39E+17 sej/year and an emergy density of 6.94E+11 sej/m²/year, reflecting high ecological productivity. The NMFR is positive (+634.000 US$/year), demonstrating net financial support, yet reinvestment is channeled predominantly into management and environmental education rather than direct ecological restoration. Notably, staff knowledge accounts for 92% of the emergy associated with the education function, underscoring human capital as a central regenerative asset. The study concludes that Mai Po's current sustainability relies on institutional stewardship rather than ecological self-sufficiency. Achieving true regeneration will require policies that mandate direct financial reinvestment into mangrove restoration and other natural capital enhancements.

Key words: Emergy Valuation, Ecosystem Services, Sustainability Indicators, Ecological Economics, Regenerative Model, Mai Po Reserve

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Introduction

Mangroves are coastal ecosystems of exceptional ecological importance, providing critical services such as coastal protection, pollutant filtration, carbon sequestration, and habitat for numerous species. In addition, they supply high-value ecosystem services, including fisheries, aquaculture, tourism, and environmental education. Despite their significance, mangrove ecosystems are among the most threatened in the world, particularly in regions experiencing intense urban and coastal development.

In this context, Mai Po Marshes, located in Deep Bay in northwestern Hong Kong, stands out as one of the last remaining mangrove areas in the region and one of the few successful examples of conservation management in an urban environment (Li et al. 2019). Covering 380 hectares, including 130 hectares of natural

mangrove and 250 hectares of tidal shrimp ponds (gei wai), the site is internationally recognized as a Ramsar Wetland and hosts over 60,000 migratory birds annually (Wang et al. 2016). Managed by WWF Hong Kong since 1983, Mai Po integrates conservation, scientific research, and environmental education, making it a model for the integration of nature and society (Young 2004; Cheung 2011).

Despite its ecological value, most assessments of Mai Po have relied on conventional economic methods that underestimate the value of non-market ecosystem services. Traditional cost-based or market-value approaches fail to capture the full contribution of nature, such as solar energy, rainfall, and biogeochemical cycles (Odum 1996). To overcome this limitation, emergy analysis offers an integrative framework that quantifies flows of energy, matter, human labor, and capital in a common unit, the solar emjoule (sej) (Odum 1983).

Emergy analysis enables the assessment of a system's true productivity by accounting for all direct and indirect solar energy required to generate a service or product. This method has been applied to various ecosystems, such as the Everglades (Brown et al. 2006; Jørgensen et al. 1995; Nadalini et al. 2021), but until the study by Qin et al. (2000), there had been no comprehensive emergy evaluation of Mai Po. In this seminal work, the authors calculated the system's total emergy flow (26.39E+17 sej/yr), its emergy density (6.94E+11 sej/m²/yr), and key sustainability indices, including the Investment Ratio (IR = 0.48), Environmental Loading Ratio (ELR = 1.03), and Yield Ratio (YR = 3.10). Notably, they also quantified the educational function of the site for the first time, revealing that its emergy (125.65E+17 sej/yr) exceeds that of the natural system itself, with staff knowledge contributing 99.26E+17 sej/yr, representing 92% of the educational investment.

This work builds on these findings to propose a conceptual innovation, the monetary counterflow model for regenerative reinvestment. In this study, monetary counterflow is defined as a financial feedback mechanism in which a portion of the revenues generated by ecosystem services, such as tourism, research, or educational programs, is directly reinvested into the restoration, maintenance, and expansion of the natural capital (e.g., mangrove forests, sediments, hydrology, and biodiversity) that originally produced those services. This concept extends Odum's (1996) observation that economic flows often move opposite to energy flows but adds a normative and destination-specific criterion: true sustainability requires that money not only oppose the energy flow but also return proportionally and directly to the ecological source. Unlike conventional conservation funding, which may support infrastructure, salaries, or outreach, the monetary counterflow is distinguished by its targeted reinvestment in natural deposits, thereby closing the regenerative loop between ecological production and financial return.

Recent advances in sustainability science have reinforced the need to link ecological integrity with financial feedback mechanisms. The UN's System of Environmental-Economic Accounting (SEEA) now provides a standardized framework for tracking ecosystem condition alongside economic flows (Edens et al. 2022), while Payments for Ecosystem Services (PES) schemes in Southeast Asia increasingly mandate direct reinvestment of tourism or aquaculture revenues into mangrove restoration (Thuy et al. 2023). Similarly, regenerative development models emphasize closing loops between natural capital production and financial reinvestment (Ellen MacArthur Foundation 2025; Wunder et al. 2025). Despite these innovations, few studies integrate such approaches with emergy-based diagnostics to assess whether monetary returns actually

regenerate the natural deposits that generate them, particularly in urban-adjacent wetlands like Mai Po, where institutional management often substitutes for ecological self-renewal (Li et al. 2019; McElwee 2025).

The objective of this study is to assess the sustainability of the Mai Po Marshes through emergy analysis and the proposed counterflow model, evaluating whether and how the money generated by ecosystem services is reinvested in the natural deposits of the system, thereby promoting long-term ecological resilience.

Methods

This study evaluates the ecological and economic sustainability of the Mai Po Marshes, a Ramsar-designated wetland in Hong Kong, using emergy analysis and a proposed monetary counterflow model. The approach follows the "top-down" systems analysis method (Odum 1996; Odum and Odum 2006), based on a system diagram that integrates renewable inputs, non-renewable inputs, and economic investments. All primary and secondary data were extracted from the comprehensive study by Qin et al. (2000), which includes a full emergy evaluation of the site, encompassing its ecological functions and educational services.

The emergy evaluation adheres to the procedures established by Odum (1996). Energy flows (solar, rain, wind, tides, and sediments) as well as economic investments such as infrastructure, government funding, and tourism income, were converted into emergy units (solar emjoules, sej) using standard transformities. The flows were categorized as follows: R, renewable sources (sun, rain, waves, terrestrial cycle); N, non-renewable sources (sediments); and F, economic investments (human resources, infrastructure, government budget, tourism). The total system emergy was calculated as the sum of all input flows is: $Total\ emergy = R + N + F$. This value also represents the system's output emergy, according to the emergy accounting principle, which assumes that all input emergy is used in the production of ecosystem services (Odum 1996). The main emergy sustainability indices were calculated, as described in Qin et al. (2000).

The Investment Ratio (IR), indicating the intensity of economic investment in relation to local natural resources is: $IR = F / (R + N)$. The Environmental Loading Ratio (ELR), which reflects the anthropogenic pressure on the system is: $ELR = (N + F) / R$. Higher values indicate greater environmental stress. The Yield Ratio (YR), which measures the system's net contribution to the economy relative to investment is: $YR = (R + N + F) / F$. Emergy Density (ED), expressing ecological productivity per unit area (sej/m²/year) is: $ED = (Emergy\ Total) / (Area\ (m^2))$.

A central component of the analysis is the education function, which was quantified in the original study as a significant ecosystem service. The emergy value of staff knowledge, derived from the educational level and experience of the 17-reserve staff, was calculated as 99.26E+17 sej/year, accounting for 92% of the total investment in the education system.

Building on this foundation, a monetary counterflow model was developed to investigate the relationship between the flow of emergy and the flow of money. The monetary counterflow is operationalized through the Net Monetary Flow Rate (NMFR), a diagnostic indicator that quantifies whether financial returns are directed toward ecological regeneration. Specifically, NMFR compares the annual monetary reinvestment in conservation with the estimated cost of environmental degradation, as detailed in Equation $NMFR = M_{reinvested} - C_{environments}$.

Crucially, only expenditures that directly enhance natural capital, such as mangrove replanting, sediment replenishment, or hydrological restoration, are considered regenerative reinvestment. Expenditures on management, education, or infrastructure, while valuable, are classified as indirect support and do not constitute a true counterflow to natural deposits. This distinction allows the model to assess not just whether money returns to the system, but where it flows within the system, a key determinant of long-term regenerative capacity.

In this model, natural deposits, such as mangroves, soils, aquifers, and biodiversity, are considered stores of natural capital that sustain the system's productivity. The dynamics of these deposits are governed by the following differential equation: $dD / dt = \alpha \cdot M_D - \beta \cdot D - \gamma \cdot P$, where D = deposit stock (emjoules), M_D = money invested in the deposit (US$/year), α = conversion efficiency (emjoules/US$), β = natural loss rate, e $\gamma \cdot P$ = anthropogenic pressure (e.g. deforestation, pollution).

To assess the financial balance of the system, two new indicators were introduced: the Monetary Valuation Coefficient (k), defined as: $k = M / E$, where M is the annual monetary value (US$/year) and E is the useful emergy (sej/year). This coefficient measures the economic value generated per unit of emergy. Furthermore, the Net Monetary Flow Rate (NMFR) has been proposed as: $NMFR = M_{reinvested} - C_{environments}$, where $M_{reinvested}$ is the monetary investment in conservation and management, and $C_{environments}$ represents the estimated cost of environmental degradation not accounted for in the market.

All emergy values, transformities, economic inputs, and aquaculture production data used in this study were directly taken or adapted from Qin et al. (2000), the only comprehensive emergy evaluation of the Mai Po Marshes to date. Accordingly, all monetary values are expressed in 1988 terms, using the exchange rate of 7.75 HK$/US$ that was in effect during that year.

While this historical baseline may not reflect current economic or exchange rate conditions, the use of a fixed reference year is standard practice in emergy accounting. It ensures consistency in energy-to-money conversions and avoids distortions caused by inflation, market volatility, or fluctuating currency values. Importantly, the purpose of the Net Monetary Flow Rate (NMFR) is not to estimate present-day financial figures but to diagnose the *direction* and *structure* of financial reinvestment, specifically, whether revenues generated by ecosystem services are channeled back into natural capital. That said, the reliance on 1988 data is a recognized limitation of this analysis. Future research should update the emergy inventory with contemporary inputs to evaluate the current sustainability and regenerative capacity of the Mai Po system.

Results

All results are derived from the emergy inventory of Qin et al. (2000), reinterpreted through the lens of the monetary counterflow model. No new primary data were collected; instead, this study offers a novel diagnostic framework applied to an existing dataset. The results of this study are presented in two parts: (1) the reproduction and analysis of the emergy indices of the Mai Po system, based on data from the original article by Qin et al. (2000), and (2) the application of the monetary counterflow model, which investigates the relationship between the flow of energy and the flow of money, with a focus on the sustainability and regeneration of natural and social capital.

Table 1 presents the main emergy flows in the Mai Po system, adapted from Qin et al. (2000). The system receives emergy from renewable (R) sources, non-renewable (N) sources, and economic investments (F).

Table 1. Emergy flows in the Mai Po system (adapted from Qin et al. 2000).

Category	Source	Emergy ($\times 10^{17}$ sej/yr)
Renewable (R)	Rain	3.98
	Waves	7.82
	Solar radiation	1.18
	Total R	12.98
Non-renewable (N)	Sediments	4.91
Investments (F)	Infrastructure and services (WWF)	4.18
	Government budget	1.84
	Tourism revenue	2.48
	Total F	8.50
Total of System (R + N + F)		26.39

Fig. 1 presents the distribution of emergy (in solar emjoules per year, $\times 10^{17}$ sej/yr) for each of the main energy sources in the Mai Po Marshes system. The most significant source is waves, with a value of 7.82E+17 sej/yr, followed by rainfall (chemical), with 3.98E+17 sej/yr, and sediment, with 4.91E+17 sej/yr. Emergy flows from human resources, such as WWF support (infrastructure and services), with 4.18E+17 sej/yr, the government budget, with 1.84E+17 sej/yr, and tourism revenue, with 2.48E+17 sej/yr, are also considerable, but lower than the natural flows. Solar radiation represents the lowest natural input, at 1.18E+17 sej/year. These data reveal that, although economic investment is essential for management, most of the emergy sustaining the system comes from natural renewable sources, highlighting the fundamental role of nature in the ecosystem's ecological productivity.

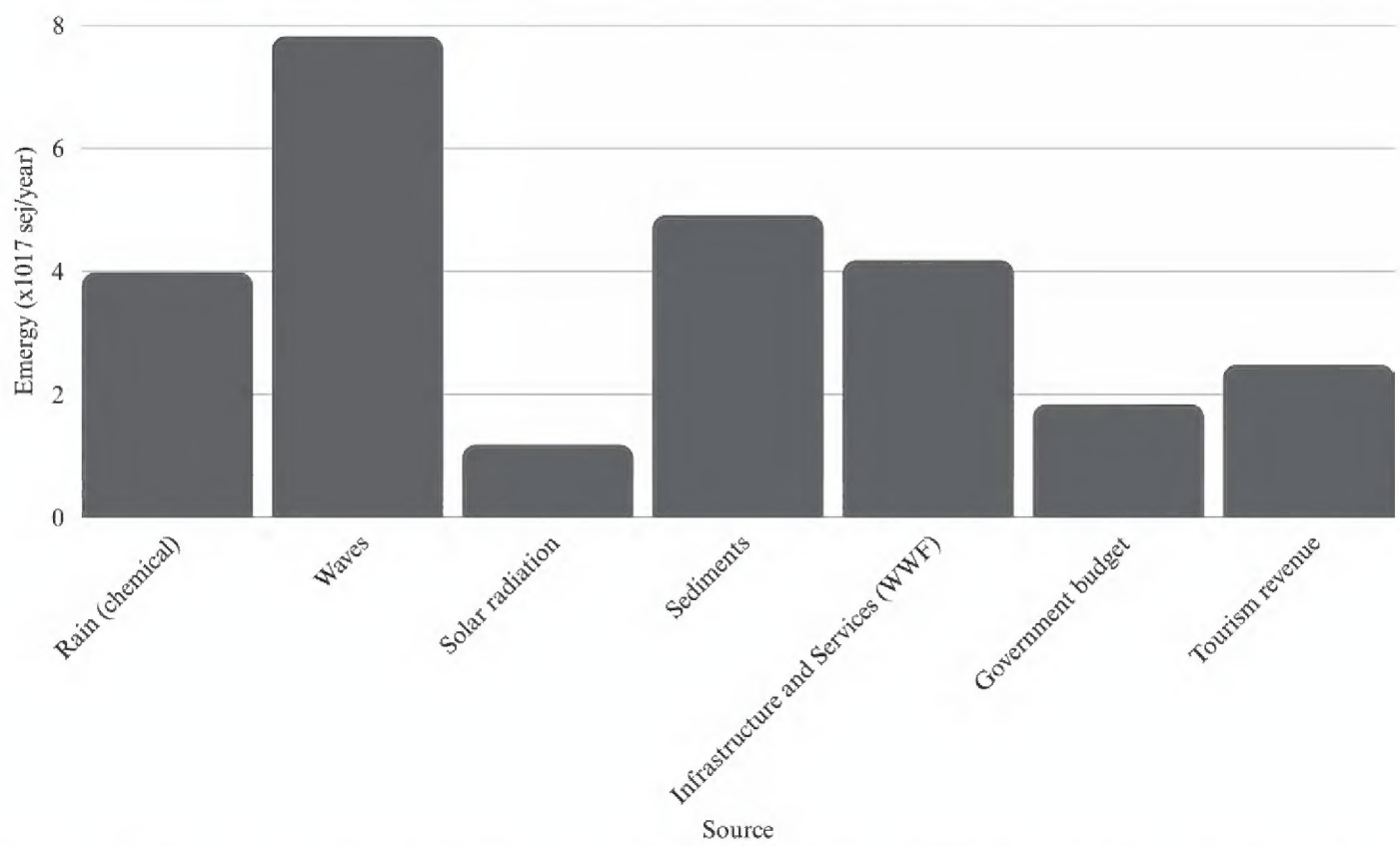

Figure 1. Emergy distribution (in solar joules per year, $\times 10^{17}$ sej/year) for each of the main energy sources in the Mai Po Marshes system.

The total emergy output of the system is 26.39E+17 sej/year, which represents both the total emergy input and output, in accordance with the principle of emergy accounting (Odum 1996). From these data, the main emergy sustainability indices were calculated. The Investment Ratio (IR) was 0.48, the Environmental Load Ratio (ELR) was 1.03, the Yield Ratio (YR) was 3.10, and the Emergy Density (ED) was 6.94E+17 sej/m²/year. These values indicate that the system is highly productive per unit area (high ED), with low relative investment (IR < 1), but faces a moderate environmental load (ELR > 1), suggesting significant anthropogenic pressure. One of the most relevant findings of the original study is the quantification of the educational function as a high-value ecosystem service. Table 2 details the components of this function.

Table 2. Emergy of the educational function in Mai Po (adapted from Qin et al. 2000).

Component	Emergy (x 10^{17} sej/yr)	Macroeconomic Value (×10^{5} US$/yr)
Environmental work	17.54	17.89
Infrastructure and services	4.10	4.18
Budget and tourism	4.32	4.24
Contribution of knowledge	99.26	97.31
Total educational function	125.22	123.62

The emergy of the education function was calculated at 125.65E+17 sej/year, significantly exceeding the emergy of the natural system itself. Of this, 99.26E+17 sej/year is attributed to the knowledge contribution of the 17 staff members, representing 92% of the total investment in the education system. This highlights the critical role of human capital as a regenerative deposit.

Fig. 2 presents the distribution of the macroeconomic value (in millions of US dollars/year) of the main components of the educational function in the Mai Po Marshes system, based on data from Qin et al. (2000). The largest share is represented by the contribution of knowledge, which corresponds to 78.7% of the total, equivalent to approximately US$97.31E+05/year, derived from the training

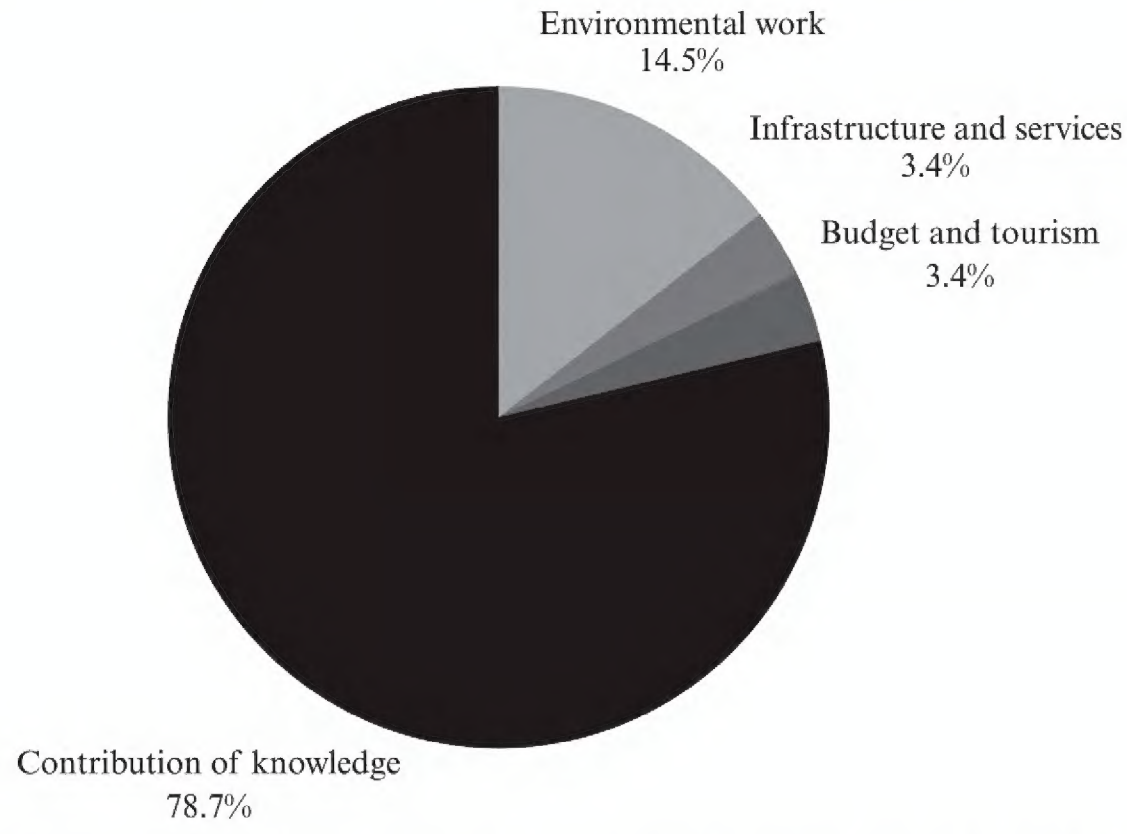

Figure 2. Distribution of macroeconomic value (in US$ million/year) of the main components of the educational function in the Mai Po Marshes system.

and experience of the 17 reservoir employees, whose emergy value was calculated based on the average intellectual productivity in Hong Kong. Second, environmental work represents 14.5% of the total value (approximately US$17.89E+05/year), reflecting the cost of direct human labor in conservation and management. The components of infrastructure/services and budget/tourism each contribute 3.4% (approximately US$4.10E+05/year), representing external institutional and financial support. These data reveal that Mai Po's educational function is not only supported by physical investments but primarily by the intangible capital of knowledge, which represents more than three-thirds of the system's total economic value, highlighting its central role as a regenerative store of value.

The monetary valuation coefficient k was calculated for the system as a whole:

$$\mathbf{k} = \frac{\textbf{Total economic value}}{\textbf{Total emergy}} = \frac{8,42 \times 10^{5}\textbf{US\$}}{26,39 \times 10^{17}\textbf{sej}} \cong 3,16 \times 10^{-13}\textbf{US\$/sej}$$

This value indicates that, on average, each sej of emergy generates about 0.316 picodollars (3.16E-13 US$). Although small, this value reflects the low direct conversion of ecological wealth into monetary value. The net monetary flow rate (NMFR) was calculated to assess whether the generated money returns to deposits: $NMFR = M_{reinvested} - C_{environmental}$.

The $M_{reinvested}$ is 8,34E+05 US$/year, including values related to tourism, budget, and services. On the other hand, $C_{environmental}$ is indirectly estimated by the high ELR (1.03) and neighboring urban pressure. A lost cost of ~2.0E+05 US$/year was assumed. Therefore: $TFML$ = 834000 − 200000 = +634000 US$/yr.

Despite the environmental burden, the NFMR is positive, indicating that the system is managed sustainably in the short term, thanks to strong support from WWF and the government. Although the NFMR is positive, there is a qualitative mismatch between the energy flows (sun, rain, and sediment → mangrove → nekton → birdlife) and the monetary flow (tourism and budget → management and education).

However, only a fraction of the money returns directly to the mangrove as active restoration. Investment in knowledge (99.26E+17 sej/year) is the main feedback mechanism, but it is indirect. This shows that the system relies heavily on social and institutional capital (WWF, government), that direct ecological regeneration (e.g., mangrove replanting) is not the primary destination for the money, and that the model is sustainable through management, not ecological self-sufficiency.

Fig. 3 is the energy diagram of the Mai Po system. The diagram shows the dynamics of energy, material, and economic value flows in the system. Emergy flows (represented by solid arrows) flow from external sources (solar, wind, rain, and tide) to the mangrove, where they are converted into primary productivity, supporting biodiversity (birds, fish, mammals) and the estuary. Water, influenced by rain, wind, and sea, circulates within the ecosystem, connecting the mangrove with coastal areas and the visitor center.

The economic value, represented by dashed lines, flows in the opposite direction to the energy flow: money from tourists, government, and external services enters the visitor center and is reinvested in infrastructure, environmental education, and WWF staff payments. One of the key findings is that, although the flow of money is significant (US$842,000/year), it does not return directly to the mangrove forest as ecological restoration but rather as management

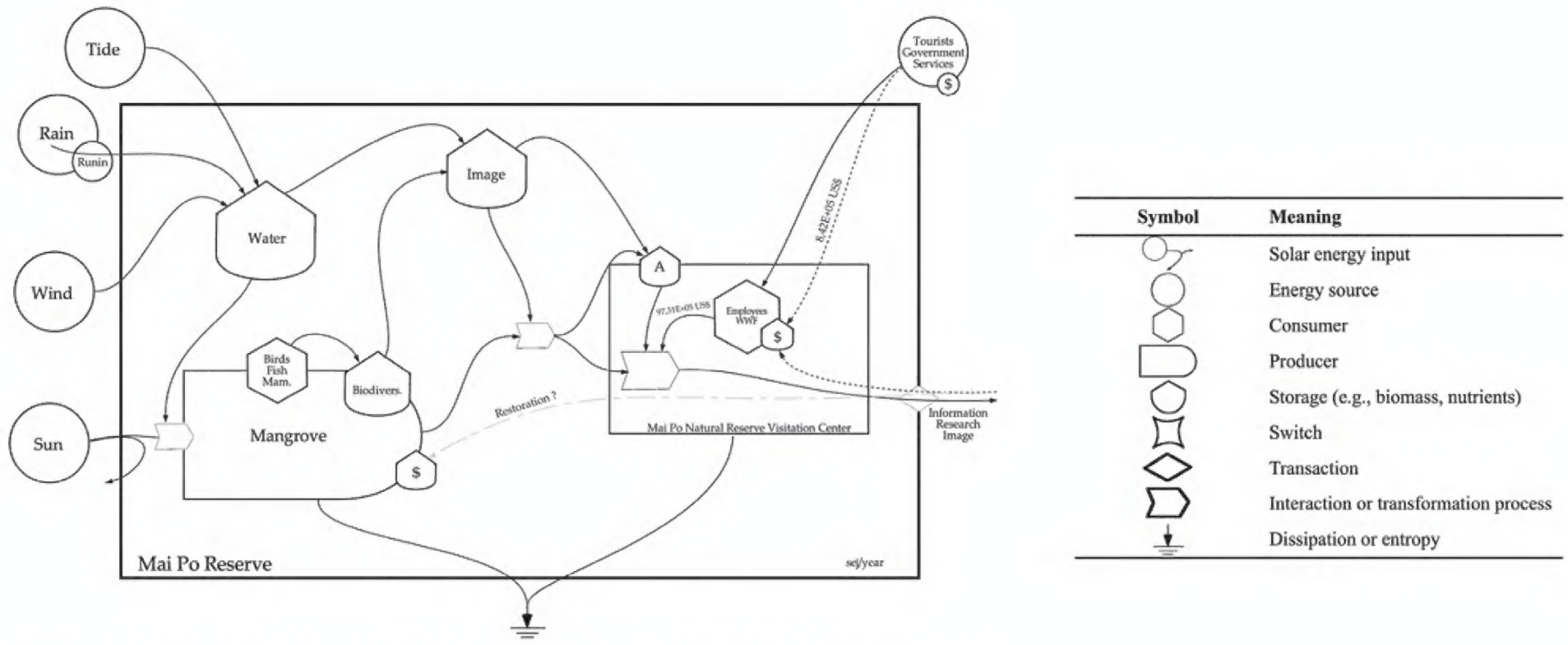

Figure 3. Energy diagram of the Mai Po system and legend of symbols used.

and education. This highlights a mismatch between the flow of emergy, which goes from the mangrove forest to the visitor center, and the flow of money to the human and institutional center. The model proposes a new vision where the monetary counterflow should be direct, with part of the money generated returning to the ecological source (mangrove forest) to promote its regeneration, closing the cycle sustainably. The lighter dashed gray line entering the system for the mangrove is shown as the system's regeneration option.

Fig. 4 illustrates the monetary counterflow model for regenerative reinvestment proposed in this study, designed to highlight the key distinction between current conservation models and a truly regenerative system. It depicts the flow of energy (solid lines) from an external energy source into the mangrove, which generates ecological services such as biodiversity, water filtration, and carbon sequestration. This energy flow is then converted into ecosystem services that are valued by tourists, government, and services, represented by a dashed line representing money ($). The Mai Po system export information, research publications, environmental education and image.

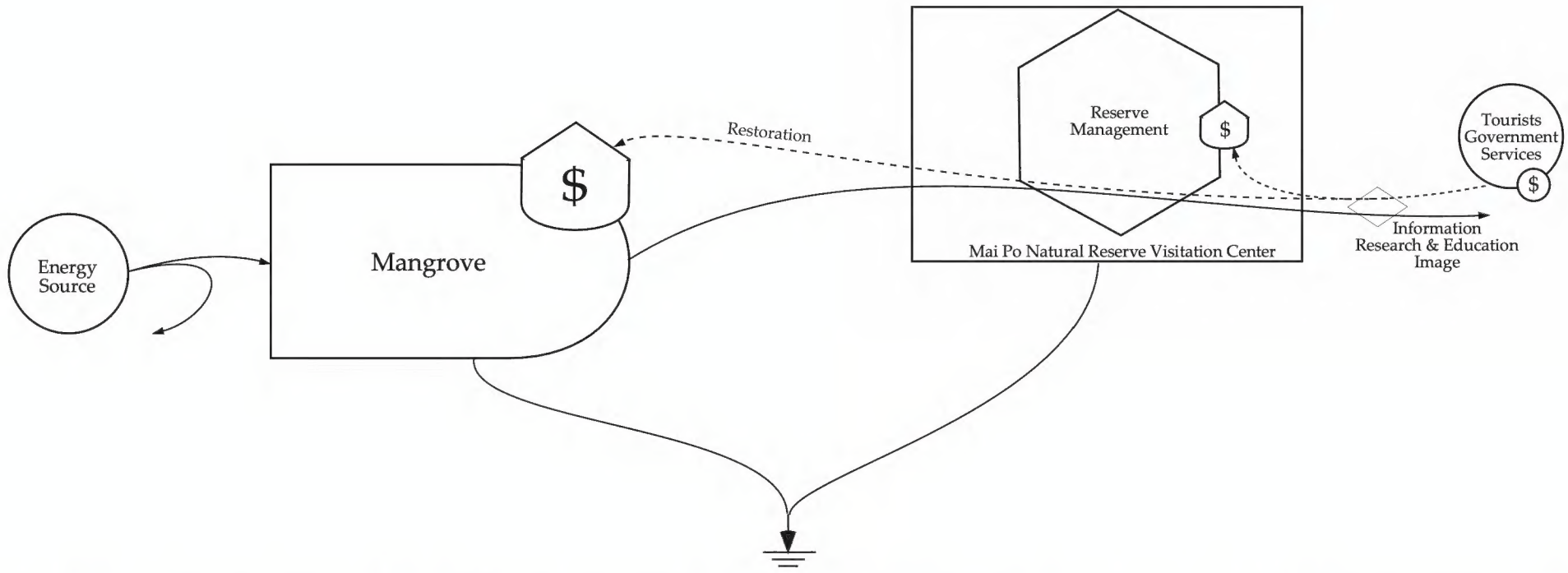

Figure 4. Monetary counterflow model for regenerative reinvestment proposed in this study. Solid line represents the energy flow and dashed lines represent the Money flow ($). The dashed gray 'Restoration' arrow represents the proposed direct monetary counterflow, a policy-design feature absent in current practice but essential for regeneration.

This monetary return flows to the Mai Po Natural Reserve Visitation Center, where it supports Reserve Management, including salaries, infrastructure, and education programs. The critical insight of the model is shown by the dashed gray line labeled "Restoration", which represents the proposed direct counterflow: a portion of the financial return should be reinvested directly into the mangrove itself as restoration activities (e.g., replanting, sediment management). This creates a closed loop between ecological production and ecological regeneration, transforming the system from one of managed conservation to one of active regeneration.

In contrast, the current model of Mai Po lacks this direct restoration link; money returns primarily to management and education, not to the mangrove. Fig. 4, thus, visually supports the conclusion that while the system is currently sustainable through institutional care, it does not fully close the loop between ecological wealth generation and its regeneration, making it vulnerable to funding fluctuations. The model proposes a new vision: for true sustainability, money must also return to its source, allowing nature to regenerate itself.

The Mai Po system demonstrates high ecological productivity per area (high emergy density), which, combined with effective management and strong institutional and educational support, presents a partial monetary counterflow, where money returns primarily as management and education, not as direct mangrove restoration. This supports the central hypothesis that money flows in the opposite direction to energy but does not always return to natural deposits proportionally to the wealth generated.

Discussion

The Mai Po Marshes exemplify a high performing yet institutionally mediated conservation model. The emergy analysis confirms that the site sustains exceptional ecological productivity, evidenced by an emergy density of 6.94E+11 sej/m²/year, placing it among the most energetically intensive coastal wetlands globally (Brown et al. 2006; Liu et al. 2021). However, this productivity coexists with moderate anthropogenic pressure (ELR = 1.03) and a governance structure that relies heavily on external financial and human capital, rather than on self-regenerating ecological feedback.

A central finding is the dominant role of human capital in sustaining the system. The education function alone accounts for 125.65E+17 sej/year, nearly five times the emergy of the natural system, with staff knowledge contributing 92% of this value. This aligns with recent work in social-ecological systems theory, which identifies skilled personnel as "living infrastructure" that enables adaptive management in complex environments (Ovando et al. 2021; Hsu et al. 2025). In urban-adjacent reserves like Mai Po, where natural regeneration is constrained by hydrological fragmentation and land-use pressure (Li et al. 2019), such human capital becomes a critical regenerative deposit. Yet, as McElwee (2025) caution, this creates dependency: when conservation hinges on discretionary funding for expert staff, it becomes vulnerable to political or economic shifts.

Despite a positive Net Monetary Flow Rate (+634,000 US$/year), financial reinvestment is directed primarily toward management, infrastructure, and environmental education, not toward direct ecological restoration such as mangrove replanting or sediment replenishment. This pattern reflects a broader trend in conservation finance, where revenues from ecosystem services often support

governance but fail to close the loop with natural capital (UNEP-Nairobi Convention/USAID/WIOMSA 2020; Thuy et al. 2023). In contrast, successful Payments for Ecosystem Services (PES) schemes in Vietnam and Indonesia legally mandate that a portion of tourism or aquaculture income be reinvested in mangrove restoration, creating enforceable regenerative feedback (Thuy et al. 2023). Mai Po's model, while effective, lacks this institutionalized reinvestment mechanism.

Our proposed monetary counterflow model seeks to address this gap by reframing sustainability as a closed-loop system: just as emergy flows from sun and tide to mangrove to birdlife, money generated by ecosystem services should flow back directly to the mangrove as restoration investment. This concept resonates with emerging frameworks in ecological economics and the circular bioeconomy, which emphasize reinvestment in natural capital to maintain system integrity (Stephenson and Damerell 2022; Ellen MacArthur Foundation 2025). It also aligns with the System of Environmental-Economic Accounting (SEEA), which calls for tracking both ecological condition and economic flows to inform policy (Edens et al. 2022).

Critically, the model distinguishes between indirect and direct counterflows. While investment in staff knowledge (99.26E+17 sej/year) constitutes a valuable indirect feedback, enhancing monitoring, education, and advocacy, it does not substitute for direct ecological reinvestment. Without the latter, the system remains ecologically hollow: rich in governance, but poor in self-renewal. This insight supports calls to move beyond "conservation through management" toward "conservation through regeneration" (Wunder et al. 2025).

From a policy perspective, these findings support the creation of regenerative financing mechanisms, such as earmarked tourism levies, green trust funds, or biodiversity bonds, that legally bind a share of ecosystem service revenues to on-the-ground restoration. Such tools are already operational in Costa Rica and the Philippines, where they have enhanced both ecological resilience and community engagement (Brownson et al. 2020). Applying similar models to Mai Po would align its management with UN Sustainable Development Goals 14 (Life Below Water) and 15 (Life on Land), which emphasize ecosystem restoration and sustainable financing (Edens et al. 2022).

It is important to acknowledge that this analysis is constrained by its reliance on 1988-based data (Qin et al. 2000). While emergy accounting requires a fixed reference year for methodological consistency, future work should update the inventory with contemporary inputs, particularly given Hong Kong's intensified urban pressures and climate risks. Nevertheless, the structural insight remains robust: without direct financial feedback to natural deposits, even well-managed reserves risk long-term degradation.

The insights from Mai Po have broad applicability to other protected coastal ecosystems, particularly those in urban or peri-urban settings where institutional management substitutes for natural resilience. The monetary counterflow model offers a transferable diagnostic framework: by calculating the Net Monetary Flow Rate (NMFR) and mapping the destination of financial reinvestment, conservation managers can assess whether their systems are truly regenerative or merely sustained through external support. This approach is especially relevant for Ramsar sites, UNESCO biosphere reserves, and community-managed mangroves across Southeast Asia, Latin America, and West Africa, where tourism and education generate revenue but rarely fund direct ecological restoration.

Moreover, the model aligns with global policy priorities. It operationalizes Target 19 of the Kunming-Montreal Global Biodiversity Framework, which calls for increased financial flows to biodiversity, and supports SDG 14.2 and 15.1, which emphasize ecosystem restoration and sustainable financing. Practically, governments and NGOs could adopt NMFR as a performance indicator in conservation contracts or certification schemes (e.g., Blue Flag for wetlands). For instance, a portion of entrance fees, carbon credits, or blue bonds could be legally earmarked for mangrove replanting, transforming passive conservation into active regeneration.

While Mai Po's data are historical, the structural insight, that money must flow back to natural deposits to close the regenerative loop, is universally relevant. The model does not require complex modeling; it only demands transparency in financial tracking and a commitment to redirecting a share of ecosystem service revenues toward on-the-ground restoration. In this sense, the monetary counterflow is not just an analytical tool but a design principle for 21st-century conservation.

Conclusion

This study demonstrates that the Mai Po Marshes are sustained by a partial monetary counterflow, in which financial resources generated by ecosystem services, through tourism, government support, and NGO funding, are reinvested primarily in institutional management and environmental education. While this model ensures short-term ecological stability, it does not direct funds toward the natural deposits, mangrove forests, sediments, hydrology, that generate the system's ecological wealth in the first place.

The emergy analysis confirms Mai Po's exceptional productivity (6.94E+11 sej/m²/year) and a positive Net Monetary Flow Rate (+634,000 US$/year), reflecting strong institutional stewardship. Yet the absence of direct financial feedback to ecological restoration reveals a structural gap: the system is conserved but not regenerated.

The monetary counterflow model for regenerative reinvestment introduced here offers a transferable framework for urban-adjacent wetlands worldwide, from the Sundarbans to the Florida Everglades, from Southeast Asian mangroves to Mediterranean lagoons. Any protected area that generates revenue from ecosystem services (e.g., entrance fees, carbon credits, research grants, or educational programs) can apply this model to diagnose whether its financial flows are truly regenerative or merely managerial.

Practically, the NMFR can serve as a simple, transparent indicator for conservation managers, policymakers, and certifiers (e.g., Ramsar, UNESCO, or Blue Flag programs) to assess the regenerative integrity of their financing. For instance, a portion of tourism income could be legally earmarked for mangrove replanting, sediment replenishment, or water quality monitoring, transforming passive conservation into active regeneration.

This approach aligns with global sustainability agendas, including the Kunming-Montreal Global Biodiversity Framework (Target 19), the UN Sustainable Development Goals 14 and 15, and the SEEA Ecosystem Accounting standards, all of which call for increased, targeted investment in natural capital. It also resonates with emerging financial instruments such as biodiversity credits, green

bonds, and community-based PES schemes, where accountability and ecological additionality are paramount.

In closing, true sustainability is not achieved when we manage nature, but when money flows back to its source, and nature regenerates itself. The Mai Po case shows that even the most successful conservation models can evolve. By institutionalizing direct reinvestment in natural deposits, we can turn today's managed reserves into tomorrow's self-renewing ecosystems.

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Conflict of interest

The author has declared that no competing interests exist.

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Data availability

All of the data that support the findings of this study are available in the main text or Supplementary Information.

References

Brown MT, Cohen MJ, Bardi E, Ingwersen WW (2006) Species diversity in the Florida Everglades, USA: A systems approach to calculating biodiversity. Aquatic Sciences 68: 254–277. https://doi.org/10.1007/s00027-006-0854-1

Brownson K, Anderson EP, Ferreira S, Wenger S, Fowler L, German L (2020) Governance of payments for ecosystem ecosystem services influences social and environmental outcomes in Costa Rica. Ecological Economics 174: 106659. https://doi.org/10.1016/j.ecolecon.2020.106659

Cheung SCH (2011) The politics of wetlandscape: fishery heritage and natural conservation in Hong Kong. International Journal of Heritage Studies 17: 36–45. https://doi.org/10.1080/13527258.2011.524004

Edens B, Maes J, Hein L, Obst C, Siikamaki J, Schenau S, Javorsek M, Chow J, Chan JY, Steurer A, Alfieri A (2022) Establishing the SEEA Ecosystem Accounting as a global standard. Ecosystem Services 54: 101413. https://doi.org/10.1016/j.ecoser.2022.101413

Ellen MacArthur Foundation (2025) Ellen MacArthur Foundation Leading the Transition to a Circular Economy. It's time for a circular economy. https://www.ellenmacarthurfoundation.org/ [November 3, 2025]

Hsu C-H, Wu Y-W, Kang J, Chiu H-K, Li M-C, Chen W-T (2025) Social-ecological memories as references for biodiversity restoration and conservation action in coastal community. Marine Pollution Bulletin 220: 118429. https://doi.org/10.1016/j.marpolbul.2025.118429

Jørgensen SE, Nielsen SN, Mejer H (1995) Emergy, environ, exergy and ecological modelling. Ecological Modelling 77: 99–109. https://doi.org/10.1016/0304-3800(93)E0080-M

Li Q, Wong FKK, Fung T (2019) Classification of Mangrove Species Using Combined WordView-3 and LiDAR Data in Mai Po Nature Reserve, Hong Kong. Remote Sensing 11: 2114. https://doi.org/10.3390/rs11182114

Liu C, Liu G, Yang Q, Luo T, He P, Franzese PP, Lombardi GV (2021) Emergy-based evaluation of world coastal ecosystem services. Water Research 204: 117656. https://doi.org/10.1016/j.watres.2021.117656

McElwee P (2025) Elements in Politics and Society in Southeast Asia Sustainable Development and the Environment in Southeast Asia. Cambridge University Press. https://doi.org/10.1017/9781108855334

Nadalini ACV, Kalid R de A, Torres EA (2021) Emergy as a tool to evaluate ecosystem services: A systematic review of the literature. Sustainability 13: 7102. https://doi.org/10.3390/su13137102

Odum HT (1983) Systems Ecology: An Introduction. John Wiley, New York, 644 pp.

Odum HT (1996) Environmental Accounting: Emergy and Environmental Decision Making. Edição: 1ª. Wiley, New York.

Odum HT, Odum EC (2006) The prosperous way down. Energy 31: 21–32. https://doi.org/10.1016/j.energy.2004.05.012

Ovando D, Caselle JE, Costello C, Deschenes O, Gaines SD, Hilborn R, Liu O (2021) Assessing the population-level conservation effects of marine protected areas. Conservation Biology 35: 1861–1870. https://doi.org/10.1111/cobi.13782

Qin P, Wong YS, Tam NFY (2000) Emergy evaluation of Mai Po mangrove marshes. Ecological Engineering 16: 271–280. https://doi.org/10.1016/S0925-8574(00)00104-X

Stephenson PJ, Damerell A (2022) Bioeconomy and circular economy approaches need to enhance the focus on biodiversity to achieve sustainability. Sustainability 14: 10643. https://doi.org/10.3390/su141710643

Thuy PT, Vi HT, Thi HN (2023) Payments for environmental services in Mangrove Forests: A review and recommendations. Multidisciplinary Reviews 6: 2023040–2023040. https://doi.org/10.31893/multirev.2023040

UNEP-Nairobi Convention/USAID/WIOMSA (2020) Guidelines on Mangrove Ecosystem Restoration for the Western Indian Ocean Region. UN Environment Programme, Nairobi, 71 pp. https://www.nairobiconvention.org/

Wang T, Zhang H, Lin H, Fang C (2016) Textural–Spectral feature-based species classification of Mangroves in Mai Po Nature Reserve from Worldview-3 Imagery. Remote Sensing 8: 24. https://doi.org/10.3390/rs8010024

Wunder S, Fraccaroli C, Bull JW, Dutta T, Eyres A, Evans MC, Thorsen BJ, Jones JPG, Maron M, Muys B, Pacheco A, Olesen AS, Swinfield T, Tegegne YT, White TB, Zhang H, zu Ermgassen SOSE (2025) Biodiversity credits: An overview of the current state, future opportunities, and potential pitfalls. Business Strategy and the Environment 34(7): 8470–8499. https://doi.org/10.1002/bse.70018

Young L (2004) Chapter 10 - Conflicts in the Management of a Wetland Nature Reserve — Case Study of the Mai Po Nature Reserve, Hong Kong. In: Wong MH (Ed.), Wetlands Ecosystems in Asia. Developments in Ecosystems. Elsevier, Amsterdam, 145–160. https://doi.org/10.1016/B978-044451691-6/50013-2

Supplementary material 1

When money should flow back to the source: A Regenerative counter-flow model in the mai po mangrove marshes

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Data type: pdf

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